PROJECT PATHFINDER

CRYOGENIC FLUID DEPOT PROJECT PLAN

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FOREWORD

Pathfinder is a research and technology initiative by the National Aeronautics and Space Administration (NASA) which will strengthen the technology base of the United States civil space program and provide options for potential future space exploration missions. These missions may include an intensive study of the Earth, a return to the Moon, piloted missions to Mars, or the continuing robotic exploration of the Solar System. Pathfinder is managed by the NASA Office of Aeronautics and Space Technology, to advance critical technologies for these missions and ensure technology readiness for future national decisions regarding exploration of the Solar System. Pathfinder extends the technological foundation being established by the Civil Space Technology Initiative, which focuses on advancing a family of technologies for transportation to and operations in near-Earth orbit and supporting science activities. Pathfinder looks toward longer-term missions beyond Earth orbit and into the Solar System.

Four major thrusts of Pathfinder are Surface Exploration technology, In-Space Operations technology, Humans-in-Space technology, and Space Transfer technology. The In-Space Operations thrust will provide the critical technologies to enable or enhance space operational capabilities in support of future piloted and robotic solar system exploration missions. A key element of this thrust is the Cryogenic Fluid Depot Program which will provide the technology base required to perform storage, supply and transfer of subcritical cryogenic liquids in a microgravity space environment.

This Program Plan describes the goals and objectives, management plan, technical approach, resources and financial management plan, facilities plan and technology transfer planning for the Cryogenic Fluid Depot element of Pathfinder. For additional information on the Cryogenic Fluid Depot Program, please contact:

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SECTION 1

EXECUTIVE SUMMARY

1.1 Program Goals and Objectives

The Pathfinder Cryogenic Fluid Depot Program will develop and validate the technologies required to perform storage, supply, and transfer of subcritical cryogenic liquids in a low-g space environment. The long-term goal of this technology program is to enable fueling and/or cryogen resupply operations for future spacecraft and space transportation vehicles in a low-g space environment.

1.2 Organization and Management

The overall program will be managed by a Program Manager in the Propulsion, Power and Energy Division (RP) of the Office of Aeronautics and Space Technology (OAST). Technology project management responsibility will reside in the Cryogenic Fluid Technology Office (CFTO) at the Lewis Research Center. Figure 2-1 depicts the current management structure for the Cryogenic Fluid Depot Program. As additional technology needs become known, additional NASA centers may become involved.

1.3 Schedule and Deliverables

By the early 1990's analytical models describing all aspects of low gravity cryogenic fluid management (including storage, supply, and transfer) will be developed and validated as much as possible with normal gravity testing. Ground-based testing of instrumentation components and processes will be largely completed. Concept formulation for a full-scale depot will have been completed as well as time-phased technology development programs in each area where critical technology deficiencies were identified.

1.4 Resources

Currently approved resources for the initial five years of the program are summarized in Table 2-1. These resources reflect the approved FY89 Congressional Budget for Pathfinder and a runout of the submitted FY89 Presidential Budget (FY90 through FY93). In the project plan, resources for FY89 are the same as in the program plan; however, the runout in the project plan reflects current planning resources. These planning resources may not necessarily reflect the runout as shown in the program plan. The project plan will be updated on a yearly basis to reflect the annual congressional appropriation.

SECTION 2

INTRODUCTION

2.1 Project Pathfinder Overview

Project Pathfinder is a National Aeronautics and Space Administration (NASA) initiative to develop critical capabilities to support the future of the U.S. civil space program. Pathfinder does not, in itself, represent a commitment to any particular mission. However, through Pathfinder, NASA's Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that can be applied to a wide range of potential future NASA programmatic thrusts: (1) Exploration, (2) Operations, (3) Humans-In-Space, and (4) Transfer Vehicles.

The Cryogenic Fluid Depot Program is one of five programs under the Operations thrust. More information on the overall Pathfinder Program can be found in the Pathfinder Program Plan.

2.2 Document Purpose and Scope

The goal of this Program Plan is to provide scope, content, and long-range plans of the Cryogenic Fluid Depot Technology Program. The objectives of this document vis-a-vis the Program are (1) to provide traceability to mission-derived technology requirements; (2) to specify the top-level work breakdown structure; (3) to define technical goals and objectives for the program and for major workpackages; (4) to define the management approach including structure, participating centers and individual roles, responsibilities, and accountability; (5) to establish resource allocations, and associated schedules, milestones, and deliverables; and (6) to document long-range Cryogenic Fluid Depot program planning.

The program includes analytical modeling, ground-based experimentation and future flight experimentation definition. Flight experimentation requirements will be defined since they are required for technology development, even though such experiments are not in the scope of this project.

Cryogenic fluid management technologies have also been identified as the most critical area for development to enable a cryogenic fluid depot. On the basis of that assessment, the overall Pathfinder Cryogenic Fluid Depot Program emphasizes the development of these technologies in the near term. Once mission studies, user needs and requirements, and depot concepts are developed, it is conceivable that additional technologies may be developed. An initial assessment of some potential technologies which may be required was performed at a workshop held at LeRC in October 1987 (Reference 1). The results of that workshop were used to develop the approximate scope for the Cryogenic Fluid Depot program.

SECTION 3

PROGRAM OVERVIEW

3.1 Mission Studies and Technology Requirements

On going NASA and Department of Defense (DOD) mission planning include spacecraft that will be launched into low Earth orbit (LEO) with limited, or no, operationally-required cryogenic fluids on board (for example, fuels such as liquid hydrogen and liquid oxygen, or coolants such as liquid nitrogen). Such a launch scenario may be preferred for a variety of reasons; these include launched mass reduction, thermal performance optimization, and risk reduction. Cryogenic fluids for these spacecraft will be transported to orbit separately, and then transferred to the user spacecraft for operations. Periodic resupply of cryogens may also be required in order to extend the useful life of the class of spacecraft or of selected payloads accommodated on the Space Station.

In order to provide a "Cryogenic Fluid Depot" capability, techniques for the long-term storage of cryogens in LEO, and elsewhere, will be required. Transfer of cryogenic fluids from storage to user-spacecraft in a low-g environment will also be required. Also, a variety of supporting service technologies, such as robotics for spacecraft manipulation during refueling, will be required.

A variety of future U.S. space missions and operations will depend upon the availability of space-based cryogen supplies. The viability of a space-based Space Transfer Vehicle (STV), for example, will require on-orbit cryogen resupply. Also, nearer-term robotic Solar System exploration missions, such as the planned Mars Rover/Sample Return (MRSR) mission, could be substantially enhanced by the capability to "top-off" upper stages in LEO.

Piloted missions to Mars will (under currently feasible scenarios) be impossible without propellant supplies at a Cryogenic Fluid Depot. Piloted Mars mission scenarios currently under study will require on-orbit assembly of the piloted spacecraft from separately launched mission elements. The total mass in LEO of such a vehicle could exceed one million pounds, 75 percent of which would be propellants, with possible additional cryogen for life support and/or temperature control. In addition, this mission would require cryogen storage for over two years to fuel return-transit staging from Mars orbit.

3.2 Technology Assessment

Three systems for managing cryogenic fluids in a space environment currently exist. First, there are small-scale storage and supply systems for superfluid helium. Second, there are small-scale supercritical fluid supply systems for hydrogen and oxygen. Lastly, there are large-scale vehicle cryogen propulsion systems. None of these systems meet critical requirements for long-term storage, supply and transfer of liquid hydrogen and liquid oxygen or the requirements of vehicle, tankage, and facility operations in a low-g space environment.

Current technology programs are focused on developing the necessary technology to develop a large-scale, space-based system to meet these requirements. Analytical models are under development, test facilities are being upgraded, and contracting efforts to perform in-space experiments are being planned.

3.3 Cryogenic Fluid Depot Program Goals and Objectives

The goal of the Cryogenic Fluid Depot Program is to develop the technology base required to perform storage, supply, and transfer of subcritical cryogenic liquids in a low-g space environment. The long-term goal of this technology program is to enable fueling/resupply operations for future spacecraft and space transportation vehicles in a low-g space environment.

Program objectives include:

(1) Development of depot conceptual designs from which critical technology areas will be identified, since the criticality of a technology depends on the depot concept assumed.

(2) Performance of critical research and advancement of technology readiness levels in the areas of fluid management and potentially in the areas of structures and materials, orbital operations and logistics, depot operations and safety. This will include large-scale ground system testing and/or analytical modeling of all critical technology items considered to be enabling to the operation of a depot.

(3) Definition of in-space experiment requirements for flight testing, even though flight experiment development is not currently covered by this program.

3.4 Technical Approach

Studies will be performed to identify cryogenic fluid user requirements and to develop cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology assessment analysis will be prepared which defines the criticality of the identified technology, assesses the current state of technology readiness and the state of technology readiness required for the development of an operational cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These assessments will be used to lay out a time-phased technology development program in each area.

The use of cryogenic fluid management technologies is inherent in all potential cryogenic fluid depot concepts. A detailed technology roadmap and program was developed under the R&T base program in FY88.

The program includes analytical modeling, ground-based experimentation and future flight experimentation definition. Flight experimentation requirements will be defined since they are required for technology development, even though such experiments are not in the scope of this project.

Cryogenic fluid management technologies have also been identified as the most critical area for development to enable a cryogenic fluid depot. On the basis of that assessment, the overall Pathfinder Cryogenic Fluid Depot Program emphasizes the development of these technologies in the near term. Once mission studies, user needs and requirements, and depot concepts are developed, it is conceivable that additional technologies may be developed. An initial assessment of some potential technologies which may be required was performed at a workshop held at LeRC in October 1987 (Reference 1). The results of that workshop were used to develop the approximate scope for the Cryogenic Fluid Depot program.

SECTION 4

MANAGEMENT PLAN

4.1 Work Breakdown Structure

The Cryogenic Fluid Depot Program is divided into six major discipline areas: (1) system integration, (2) fluid management, (3) depot operations, (4) structures and materials, (5) orbital operations and logistics; and (6) safety. Figure 2-2 provides an overview of the work breakdown structure. The system integration element will define requirements, provide conceptual designs, assess technology impacts and mission benefits which will lead to reference system designs. The Fluid management element will develop the technology base which will enable the design of efficient systems for managing subcritical cryogenic fluids in a low-g space environment. The depot operation element will develop the technology base required for a cryogenic fluid depot to support its primary operational function of storing and supplying cryogenic propellants and other fluids for NASA/DOD launch systems, satellites, and space station. The stuctures and materials element will identify depot-unique technology requirements for structures and materials that are beyond the current state-of-the-art, to assess the criticality of any technology shortfalls to the depot program, and to develop an advanced technology development plan. The orbital operations and logistics element will provide the technology base that will enable the routine utilization of a fuel depot by the NASA space fleet and the effective functional support by, and for, the depot facility. The safety element will develop the technologies necessary to assure safe and reliable operation of a space-base fuels depot.

4.2 Organization and Management Structure

The overall program will be managed by a program manager in the OAST Propulsion, Power and Energy Division (RP). Technology project management responsibility will reside at LeRC in the Cryogenic Fluid Technology Office (CFTO). The program manager will have the responsibility of coodinating with other programs and Pathfinder elements to avoid duplication of efforts and to ensure that all technologies are being adequately addressed. The project manager will have the responsibility within the program of insuring that specific technology efforts are coordinated through matrixed responsibilities in each technology discipline. The project manager will utilize discipline branches within the LeRC Cryogenic Fluid Technology Office as well as expertise available in the LeRC Advanced Space Analysis Office, and the Johnson Space Center (JSC) and other NASA Centers as appropriate. Figure 2-1 depicts the current management structure for the Cryogenic Fluid Depot Program. As additional technology needs become known, additional NASA Centers may be involved. LeRC will have responsibility for leading the development of a technology project plan and for implementation of the plan throughout the program. All participating centers will be responsible to the project manager for all matters including resources, program responsibilities, and administrative duties pertaining to reporting, schedule and milestones.

4.3 Program Coordination

The Cryogenic Fluid Depot Program will be closely coordinated with the Office of Space Flight (OSF). Within OAST, coordination will be maintained with the on-going CSTI programs in the area of automation and robotics in OAST/RC, with OAST/RM in the area of materials and structures, and with OAST/RX in the area of flight experimentation. In addition to mission analyses and requirements definition within the program, this effort will also be coordinated with the mission planning activities of the Office of Exploration (OEXP), the Office of Space Science and Applications (OSSA), the Office for Space Operations (OSO), and the Office of Space Station (OSS).

As appropriate, mission enhancements through technology applications will be recommended to those offices. A systematic approach to the technology issues associated with the development of a cryogenic fluid depot will begin with the definition of the system requirements. These requirements will be generated by those missions which a depot will support. These requirements will be collected from the user organizations (Codes C, E, M, S, Z) and cataloged in a database. Depot conceptual designs that satisfy these requirements will be generated from which critical technology areas can be identified. Coordination across organizations in these efforts will insure consistency of these depot concepts with mission plans.

4.4 Program Planning and Documentation

4.4.1 Cryogenic Fluid Depot Project Plan

A detailed five-year project plan (with less detailed extensions to ten years) will be developed. The project manager will be responsible for producing and implementing the plan. The project manager shall coordinate the planning activities with the other participating centers and with OAST. The authority to resolve conflicts will reside with the program manager. The project plan will document program content, center responsibilities, resource allocations, and milestones. Project reviews will be held twice each year. During these reviews each center will participate in the review in their particular areas of R&T. The project plan will be modified as required.

4.4.2 Memorandum of Agreement (MOA)

A memorandum of agreement (MOA) will be established between OAST and OSF to provide for the cooperation and implementation of cryogenic fluid technology R&T and advanced development programs that will support the achievement of agency objectives.

The OSF program depends on the OAST technology program for cryogenic research technology. The technical expertise of all participants must be available to any phase and any aspect of either program.

The MOA will provide a formal structure for the coordination of the two programs to assure that the required technologies are identified and defined, that they are developed in a timely and focused manner, that the knowledge and expertise existing in both the OAST and OSF programs is communicated to all parties, and that the available program resources are fully utilized while avoiding duplication.

4.5 Program Reviews and Reporting

The lead center project manager will conduct periodic reviews with the program manager. These reviews will report on how planned key milestones are achieved, and will assure that OAST is informed as to program status and resources expended and required. These reviews will be held a minimum of twice each year. Additionally, following the annual RTOP submittal, a formal summary presentation will be made to the program manager indicating prior year accomplishments versus planned milestones. The project management information and control system (MICS) method of management reporting will be used to report the program status to the program manager.

The MICS reporting system will provide selected information required to ensure accountability for status, indicate trends, report on actions and changes, depict manpower and illustrate funding requirements as appropriate. Selection and level of information will be egreed on between the program manager and the project manager. Each quarterly report will cover all significant project aspects, including technical progress and management areas such as funding and procurement. Emphasis will be placed on identifying problem areas in a timely fashion and developing and implementing corrective actions.

4.6 Advisory Committees and Working Groups

The Depot Coordination Committee will be utilized as an advisory group for planning and coordination of the overall Cryogenic Fluid Depot program. The Cryogenic Fluid Program Coordination Committee will be formed as the guiding body for planning and coordination between the cryogenic fluid technology development program (OAST) and advanced development activities (OSF). It is anticipated that working groups will be created by the committees to advise on specific technical areas as necessary.

SECTION 5

TECHNICAL PLAN

5.1 Summary of Deliverables

By the early 1990's analytical models describing all aspects of low gravity cryogenic fluid management (including storage, supply, and transfer) will be available and validated to the degree possible with normal gravity (one-g) testing. Ground-based testing of instrumentation, components, and processes will be largely completed. Flight experiment requirements definition will be completed. Concept formulation for a full-scale depot will have been completed as well as time-phased technology development program in each area where critical technology deficiencies for a depot were identified.

5.1.1 Five Year Schedule and Milestones

A five-year schedule is provided in Figure 2-3; major milestones are listed in Table 2-2. The schedule and milestones shown indicate activities only in cryogenic fluid management and on system integration, depot system technology assessment, with areas to be determined (TBD) shown in the other program elements pending completion of the technology assessment tasks.

5.1.2 Technology Readiness Objectives

Table 2-2 indicates the technology readiness level assessed at this point in the program. It also indicates the technology readiness level required to establish a technology database adequate for the design of a depot and the level to which this program will advance those technologies. To advance the technology readiness levels to the level required will necesitate the conduct of in-space experimentation in most technology areas.

5.1.3 Technology Performance Objectives

A systematic approach to the identification of technology issues of a space-based cryogenic fluid depot will begin with the identification of the system requirements. These requirements are generated by the missions which a depot will support. These requirements will be collected from the user organizations (Codes C, E, M, S, and Z) and cataloged in a database. The requirements are expected to include at least the types and quantities of cryogenic fluids required, the location in which they are required, the duration of the storage time, receiving frequency, etc.

5.2 System Integration

5.2.1 Objective

The objective of this element of the Cryogenic Fluid Depot Program is to define requirements, provide conceptual designs, assess technology readiness, and provide subsystem trades identifying technology impacts and mission benefits which will lead to reference system designs.

5.2.2 Technical Approach

A systematic approach to the technology issues of a space-based fluid depot will begin with the definition of the system requirements. These requirements will be generated by those missions which will be supported. These requirements will be collected from the user organizations, Codes C, E, M, S, Z, and cataloged in a database. Depot conceptual designs that satisfy these requirements will be generated from which critical technology areas will be identified.

The next phase of these studies will involve the assessment of technology readiness where critical technologies have been identified. Technology development plans will be formulated for those technology areas identified as both critical to a depot and those which currently lack the appropriate technology maturity. Refinements to a detailed work breakdown structure will be made as appropriate. The studies will also identify alternate technology options which may require trade studies to quantify system advantages and disadvantages.

5.2.3 Description

The initial phase of studies will involve the gathering of depot system requirements from the user community. Documents containing this data will be obtained from the Offices of Space Science and Applications, Space Station, Space Flight, and Exploration. Interviews with cognizant individuals of these organizations will also be conducted.

Conceptual designs for a depot will be generated that meet the user's requirements. This aspect of the studies will require close coordination with Code Z mission planning efforts at LaRC which is developing conceptual designs to meet various missions. If these designs are at a level sufficient to identify technology issues, they will be incorporated into these studies.

Since the criticality of a technology depends on the depot concept assumed, these studies will analyze several depot concepts and their effect on technology requirements. Coordination in these efforts with the Office of Exploration and the Office of Space Station will insure consistency of these depot concepts with current agency planning.

Using the "On-Orbit Fuels Depot Technology Roadmap" report (ref.1) as a point of departure, the technologies identified as high criticality and low maturity will be assessed in more detail. This assessment will entail a more specific definition of the technology requirements levied on a depot, contact with discipline experts will be made to assess the technology state-of-the-art, to develop the required technology development program, and to estimate schedules and program costs.

5.3 Fluid Management

5.3.1 Objectives

The objective of this element is to develop the technology base which will enable the design of efficient systems for managing subcritical cryogenic fluids in a low-g space environment.

5.3.2 Technical Approach

The critical technologies to be developed were identified based upon a review of the future NASA and DOD mission plans. cryogenic fluid management technology requirements were grouped into six general categories of 1)liquid storage, 2) liquid supply, 3)fluid transfer, 4)fluid handling, 5) tank structures and materials; and 6) advance instrumentation. Each of these broad technology areas was further subdivided and reviewed for relevance at a workshop held at LeRC April 1987 (ref.2). The approach which will be used to develop the required technologies includes: 1)analytical modeling of the important technological processes, 2)ground-based testing; and 3)in-space experimentation. Liquid hydrogen will be the primary test fluid for ground-based experimentation and the preferred fluid for in-space experimentation.

5.3.3 Description

The three major program elements are (1) developing analytical models describing the various governing processes, (2) performing a series of ground-based experiments, and (3) formulating in-space experimentation requirements. Ground-based experiments will provide limited validation of the analytical models.

Analytical model describing the key processes expected to influence the storage, supply and transfer of subcritical cryogenic fluids in the space environment will be developed. The analytical modeling effort consist of 1) prototype analytical modeling developed in-house at LeRC from first principles, 2) complementary modeling supported by grants, interagency agreements, and contracts and 3) an integrated system-level modeling effort in which the prototype modeling is combined with the complementary modeling to create a user-friendly computer code (CRYOTRAN) to predict fluid and thermal behavior of cryogenic systems in the low-gravity space environment. The analytical models will be documented and disseminated to the user community. These computer codes, once validated, will be used to aid the designers of operational space-based cryogenic systems.

Ground-based experimentation will be performed at LeRC, at university and contractor sites under grants and contracts, and potentially at other NASA centers. These experiments are expected to range from fundamental process evaluations to system-level experimentation. They will include fundamental studies of interfacial heat and mass transfer, Joule-Thompson expander characterization, chill-down and non-vented tank filling, tank pressure control, thermal stratification, liquid sloshing, insulation system evaluation, quantity mass gauging testing, fluid mixing, pressurization (both autogenous and non-condensible), thermal sub-cooling, sub-cooled or slush hydrogen transfer, mass flowmetering, screen acquisition degradation, and cryogenic instrumentation assessments. These tests are anticipated to involve cryogenic nitrogen and hydrogen as well as other fluids such as water and certain refrigerants.

In-space experimentation requirements will be formulated, even though funding for flight experiments is beyond the scope of this program. Space experiments will be necessary to generate additional data for those processes and technologies requiring the low-gravity environment for validation.

5.4 Depot Operations

5.4.1 Objectives

The objective of this element is to develop the technology base required for a cryogenic fluid depot to support its primary operational function of storing and supplying cryogenic propellants and other fluids for NASA/DOD launch systems (STV, lunar, Mars, etc.), satellites, and Space Station.

5.4.2 Technical Approach

Prior studies and workshops (refs. 1 and 2) have formed the basis of a technology assessment related to depot operations as well as overall aspects of depot concept. Technologies critical to the depot and their technology readiness levels were identified. This work will be extended via workshops and more extensive assessments. Also, further definition and focus will result from the baseline concepts definition and systems analyses efforts. The necessary technologies for supporting depot operations to be selected for inclusion in the program will be determined on the basis of criticality to the depot, technology readiness level, and whether or not it is applicable to other space applications.

5.4.3 Description

Technologies relevant to the "Depot Operations" WBS category are those concerning the general "housekeeping" functions of the depot and with enabling the depot to perform its necessary functions. Examples include attitude and thermal control, station-keeping, vibration control, and those relating to propellant manufacturing and vehicle servicing, if applicable.

Specific technologies identified to date include the following:

Automated Operation/Robotics
Automated Vehicle and Payload Processing
Large Flexible Structure Control
Space Power (500 KW)
Artificial Gravity Generation
Attitude Control by Momentum Management
Mass Properties Management
Oxygen/Resistojet (Propulsion)
Supercritical Tanks
Vibration Control
On-Orbit Assembly of Insulation
On-Orbit Tank Assembly
Water Electrolysis
Attitude Control by Superconductor

5.5 Materials and Structures

5.5.1 Objective

The objective of this element is to identify depot-unique technology requirements for structures and materials that are beyond the current state-of-the-art, to assess the criticality of any technology shortfalls to the depot program, and to develop an advanced technology development plan that assures technology readiness in a time frame consistent with depot planning.

5.5.2 Technical Approach

The materials and structures requirements for a depot will be identified from the conceptual designs developed in Section 5.2. Assessments of the level of readiness of these technologies will be made and programmatic recommendations made where deficiencies are identified.

5.5.3 Description

An initial assessment will be conducted of the requirements imposed on structures and materials technologies by a full-scale space-based depot. The unique technical challenges associated with a structure of several hundred meters in length supporting tanks containing millions of pounds of cryogenic fluids will be documented in areas such as:

Tank structural integrity
Coatings and sealants
Long-life space environment materials and components
Storage bladders
Micrometeroid/debris protection
Components vacuum jackets

This assessment will use the findings of the On-Orbit Depot Technology Workshop, and will extend the work by literature searches and interviews with experts to verify assessments of technology criticality and maturity.

5.6 Orbital Operations and Logistics

5.6.1 Objectives

The objective of this element is to provide the technology base that will enable the routine utilization of a fuels depot by the NASA space fleet and the effective functional support by, and for, the depot facility.

5.6.2 Technical Approach

A study will be conducted to assess the new requirements that an orbiting depot will impose upon orbital operations and logistics. Those technology requirements that are beyond current capabilities will be identified and assessments will be made of their state of maturity. Where technology readiness gaps are identified, advanced development plans will be formulated including schedules and funding requirements.

5.6.3 Description

Typical orbital operations scenarios involving utilization of a fuels depot will be generated and the associated logistics requirements will be defined. From these orbital operations and logistics models, those activities determined to require technologies beyond the current state-of-the-art will be cataloged. Technology areas to be addressed will include but not limited to:

Advance assembly techniques
Advanced extra vehicular activity (EVA) suit
Advanced or autonomous rendezvous techniques
Artificial intelligence for proximity operations
Expert systems
Automated logistics management

The assessments and determinations described above will involve literature searches and meetings with experienced experts in the field of orbital operations and logistics and will represent consensus opinions. As a minimum, the expertise of operations personnel from OSF centers and technology developers from OAST centers will be utilized.

The focus of this effort will be to identify depot-unique requirements that are not presently being addressed by NASA programs. When critical technologies with low maturity levels are identified, estimates of development time and costs will be determined.

5.7 Safety

5.7.1 Objectives

The objective of this element is to develop the technologies necessary to assure safe and reliable operation of a space-based fuels depot.

5.7.2 Technical Approach

The safety issues associated with the storage and handling of large quantities of potentially explosive fluids in both gaseous and liquid states will be addressed by means of workshops, interviews, and literature searches. The safety aspects of ground operations, the launch phase, and orbital operations will be studied with emphasis on the latter two.

5.7.3 Description

Because of the potentially explosive nature of the fluids, the large quantity possibly located in close proximity to the U.S. space station or any other space-based facility (i.e. Lunar mining operation facilities) and the lack of an experience database for a space-based depot, there will be need for safety assurance systems currently beyond the state-of-the-art. A study will be conducted to identify safety issues, develop concepts that address these issues, and determine the development programs required to bring these technologies to suitable readiness levels to insure safe operations of a depot system in the proper time frame.

Many safety issues are intimately associated with operations. Therefore, coordination and cooperation are necessary with JSC, MSFC, and KSC for success in this study. Additionally, close coordination with the Office of Safety, Reliability, Maintainability and Quality Assurance (Code Q) will be maintained throughout this study.

5.8 Long Range Program Plan & Options

By mid-to-late 1990's, ground-based validation of subsystems and integrated cryogenic fluid management analytical models will be completed. The ground-based subscale depot demonstration will be in progress. If subsequently approved, a cryogenic fluid management flight experiment may be implemented by late 1990s.

SECTION 6

RESOURCES AND FINANCIAL MANAGEMENT PLAN

6.1 Five Year Funding Requirements

Projected resources to meet the goals and objectives of the Cryogenic Fluid Depot Technology program for fiscal year 1989 through 1993 are approximately $25 million. The resources allocation for the program for FY1989 will be $3 million. Resources for the first five years of the program are summarized in table 2-1.

6.2 Five Year Workforce Requirements

Table 2-1 provides the estimated personnel requirements for the first five years of the program.

6.4 Contracting Plans

The Cryogenic Fluid Depot element of Pathfinder will utilize in-house NASA expertise as appropriate to the Depot disciplines discussed in Section 5. To supplement in-house expertise contracts will be established with the industry. Utilization of university research talent in the area of fluid management process modeling will contribute significantly to the effort. Other government organizations such as JPL, National Bureau of Standards (NBS), and Los Alamos National Laboratory (LANL), and other NASA centers, such as JSC, are expected to be part of this effort through appropriate instruments. These organizations, in cooperation with NASA personnel, will perform the needed studies, designs and hardware tests. In-house research and technology efforts will be supported by support service contracts as appropriate.

SECTION 7

FACILITY PLANS

7.1 Overview

The facility requirements anticipated for the Pathfinder Cryogenic Fluid Depot element are classified into those required for zero-gravity environment and those required for one-g data points for verification of modeling activities and integrated system demonstration.

7.2 Facilities Assessment

The zero-g facility will be use as appropriate to evaluate fluid dynamics problems, which can be examined using referee fluids such as alcohols and freon. Potential study areas include flow patterns and spray nozzle characterization and fluid mixing during tank fill.

The one-g facilities will provide data points for validation of modeling activities in the areas of chilldown and no-vent fill, tank pressure control such as thermodynamic vent systems and fluid mixers, and high performance multi-layer insulation (MLI) insulation system tests with and without vapor cooled shields.

7.3 Demonstration Facilities & Testing

Simulating the zero-g environment for short periods of time is an operation requiring no innovative facilities. No unique requirements are envisioned, other than those associated with building the capabilities to test a high fidelity depot model in a simulated space environment to establish overall system thermal performance. All the ground-based (one-g) experimentation will be conducted in existing facilities, some of which will need to be modified or refurbished as required.

SECTION 8

TECHNOLOGY TRANSFER PLANNING

8.1 Overview

The technology developed during the Cryogenic Fluid Depot element of Pathfinder will be disseminated to the technical community through planned workshops, reviews, publications, and conference presentations. The participation of the fluid management community through contracts and grants will insure a transfer in a timely fashion.

APPENDIX B

Memorandum of Agreement

MEMORANDUM OF AGREEMENT

BETWEEN THE OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY AND THE OFFICE OF SPACE FLIGHT FOR CRYOGENIC FLUID PROGRAMS

I. PURPOSE

This Memorandum of Agreement (MOA) is established between NASA's Office of Aeronautics and Space Technology (OAST) and Office of Space Flight (OSF) to provide for the implementation of cryogenic fluid technology and advanced development programs that will support the achievement of Agency objectives. The programs are interactive. The OAST research program, conducted primarily at LeRC, develops the basic and focused cryogenic technology and transfers it to the OSF for incorporation in development programs, conducted primarily at MSFC. As the OSF development programs proceed, the supporting test activities will produce information that is useful to the OAST technology program. The technical expertise of all participants must be available to any phase and any aspect, of either program. This MOA is intended to provide a formal structure for the coordination of the two programs.

II. BACKGROUND

OAST is conducting programs to develop the technologies required for the efficient management and utilization of cryogenic fluids in the space environment. Included in these programs are technologies for the storage, supply, transfer, instrumentation, and management of cryogenic propellants. It is anticipated that these programs will continue until all technology requirements for NASA programs have been met.

OSF is conducting studies of a Space Transfer Vehicle (STV) with the goal of developing an interim cryogenic vehicle in 1998 that has the capability to be fully space-based when the space facilities are available. In support of the STV program, OSF is conducting advanced development activities that will apply cryogenic technologies in the design of the STV.

Both OAST and OSF anticipate that flight experiments will be required to obtain some technical data that cannot be simulated in ground tests. Additionally, one or more ground-based test beds will be required.

Both OAST and OSF have responsibilities to support planning and development activities in support of proposed new initiatives currently under study by the Office of Exploration and the Office of Space Sciences and Applications. It is anticipated that an initial orbital transportation node will be required sometime in the late 1990's or early 2000 time period to support these missions. OAST, OSF and the Office of Space Station have responsibilities for planning the technologies, operations and facilities that will be required.

III. SCOPE, DURATION, AND MAINTENANCE

This MOA covers all OAST cryogenic fluid management technology development activities and all OSF cryogenic advanced development activities in support of in-space cryogenic systems design and development efforts. This MOA will remain in effect until altered or terminated by mutual agreement of the participating offices.

IV. RESEARCH OPPORTUNITIES

One objective of in-house research and development activities is to maintain and increase the technical expertise of NASA employees. OSF and OAST agree to make research opportunities available to all program participants, including the opportunity for participants in one program to serve as co-investigators on ground and flight experiments sponsored by the other program, and to disseminate the research results widely.

V. PROGRAM TASKS

OAST is responsible for cryogenic fluid management research and technology development programs including required modeling, analysis, ground and space based experimentation to develop the technologies to a level of maturity suitable for transfer to the OSF advanced development programs. OSF is responsible for development of space transportation systems including ground or space based advanced development efforts required to incorporate the appropriate technologies. OAST and OSF recognize that the theoretical division of responsibilities discussed above will not always be easy to interpret in practice and that the overriding principle is that NASA should have the most efficient and cost-effective program. To that end, OAST, OSF and the participating centers will coordinate task structuring and task responsibilities through a coordination committee (Section IX). Where appropriate, the task agreements will be formalized by inter-Center Memoranda of Agreement.

VI. TEST FACILITIES

OAST and OSF agree to minimize the duplication of equipment and effort to the extent practical considering differing program objectives and logistical problems. In the design, construction, and operation of ground based and space based facilities, every attempt will be made to satisfy the needs of both the OSF and OAST programs on a non-interference basis.

VII. FLIGHT EXPERIMENTS

Flight experiments will be required to achieve both OAST and OSF objectives. OAST and OSF will coordinate the planning for these and will conduct joint experiments if, after consideration of the objectives and schedules, this seems in the best interest of the Agency. OSF will provide OAST with a technology needs list based on advanced development and system design critical need dates. OAST will endeavor to provide the basic technologies required to support OSF system development activities in a

X. MOA SIGNATURE AUTHORITY

The parties signatory to this document agree to the scope and intent of this document without reservations and agree to enforce its implementation and application. This MOA is agreed to this ______________ day of ________, 1988. The agreement is in effect from this date until termination by the signatures of the Associate Administrators of OAST and OSF.

______________________________	______________________________
Associate Administrator Office of Aeronautics and Space Technology	Associate Administrator Office of Space Flight

timely manner. In general, OAST will schedule and develop those flight experiments needed to develop the cryogenic fluid technologies required for future NASA programs. OSF will schedule and develop flight experiments that are needed to support specific system development activities.

VIII. FUNDING

This MOA does not provide for exchange of funds or for jointly funded projects. However, these are not precluded in the future. Provisions for these can be made by amendment to this agreement.

IX. CRYOGENIC FLUID PROGRAMS COORDINATION COMMITTEE

This Memorandum of Agreement also establishes the Cryogenic Fluid Programs Coordination Committee as the guiding body for planning and coordination of the cryogenic fluid technology and advanced development activities. The charter for this Committee, including the designation of chairperson and members, is included as Attachment A to this MOA. It is anticipated that the working groups will be created by the Committee to advise on specific technical areas. It is also anticipated that the chairperson will be asked to represent this Committee on a Steering Committee for the Space Transfer Vehicle.

ATTACHMENT A

CHARTER FOR THE CRYOGENIC FLUID PROGRAMS COORDINATION COMMITTEE

1.0 OBJECTIVE

This document constitutes the charter for the Cryogenic Fluid Programs Coordination Committee.

2.0 AUTHORITY

The Cryogenic Fluid Programs Coordination Committee.is formed at the direction of the Associate Administrator for OAST and the Associate Administrator for OSF.

3.0 FUNCTIONS

3.1 The Committee will coordinate the OAST and OSF cryogenic fluid management programs to assure that Agency needs are met. The Committee will review the major program objectives, schedule considerations and implementation plans.

3.2 The Committee will assure proper planning and coordination of the ongoing cryogenic fluid management program efforts at LeRC and MSFC. At least once a year, the Committee will conduct program reviews to assess current year progress and accomplishments, review plans for the subsequent fiscal year and make recommendations as appropriate.

3.3 The Committee may assign actions and require reports on these as required to assure coordination and accomplishment of objectives.

3.4 As required, the Committee will inform senior management of the current status, the Committee's recommendations, and future plans for cryogenic fluid management programs.

3.5 From time to time, the Committee may establish Technical Working Group(s) to assist in adequately evaluating current technical accomplishments and future plans and in reassessing technology requirements for cryogenic fluid management programs to meet Agency needs.

4.0 MEMBERSHIP

Membership of the Committee will be composed of full-time managers and employees of the Federal Government. The Committee will have a standing membership which can be changed by majority votes of members. The initial membership of the Committee is set forth in Attachment B.

5.0 MEETINGS

5.1 Meetings of the Committee will be held at the call of the Chairperson and will not be held less than annually. A quorum of the Committee will be at least half of the members plus one. If circumstances arise where a quorum from the standing membership cannot be present and a Committee meeting must be held, the Chairperson has the authority to draw upon members from the alternate list contained in Attachment B or to designate personnel who are full-time officers or employees of the Federal Government to participate as members of the Committee on a temporary basis. In all cases, the alternate committee member shall be a member of the same organizational unit as that of the absent standing committee member.

5.2 The Executive Secretary of the Committee is responsible for scheduling meetings, establishing agendas, ensuring that a quorum will be present and arranging for appropriate technical minutes to be recorded.

5.3 Minutes of each meeting will be recorded and will contain as a minimum:

a. The attendance list
b. The agenda
c. A summary of matters discussed and conclusions reached

d. A list of all action items assigned and due dates

e. Committee recommendations and assessments

f. Minority views when recommendations or assessments are not unanimous

g. Copies of all documents received, issued or approved by the Committee

5.4 The accuracy of all minutes will be verified by concurrence of the Chairperson. Copies will be sent to all members.

6.0 COMMITTEE RECORDS

All records and files of the Committee, including agendas, meeting minutes, studies, analyses, reports, working papers and other documents will be made available to, or prepared by or for the Committee and will be retained by the Executive Secretary of the Cryogenic Fluid Programs Coordination Committee.

ATTACHMENT B

CRYOGENIC FLUID PROGRAMS COORDINATION COMMITTEE MEMBERSHIP

Chairperson:	Director, Propulsion, Power and Energy Division/OAST
Executive Secretary:	Program Manager, Cryogenic Fluid Management Technology/OAST
Members:	Director, Flight Project Division/OAST Director, Advanced Program Development Division/OSF Manager, Cryogenic Fluid Technology Office/LeRC Director, Propulsion Laboratory/MSFC Director, Preliminary Design Office, Program Development/MSFC
Alternates:	Deputy, Propulsion, Power and Energy Division/OAST (Alternate Chairperson) Program Manager, Cryogenic Fluid Management Flight Experiment/OAST Manager, Advanced Upper Stages/OSF Deputy Manager, Cryogenic Fluid Technology Office/LeRC Chief, Space Propulsion Branch of the Propulsion Laboratory/MSFC Representative, Structures and Thermal Analysis Branch, Preliminary Design Office, Program Development/MSFC

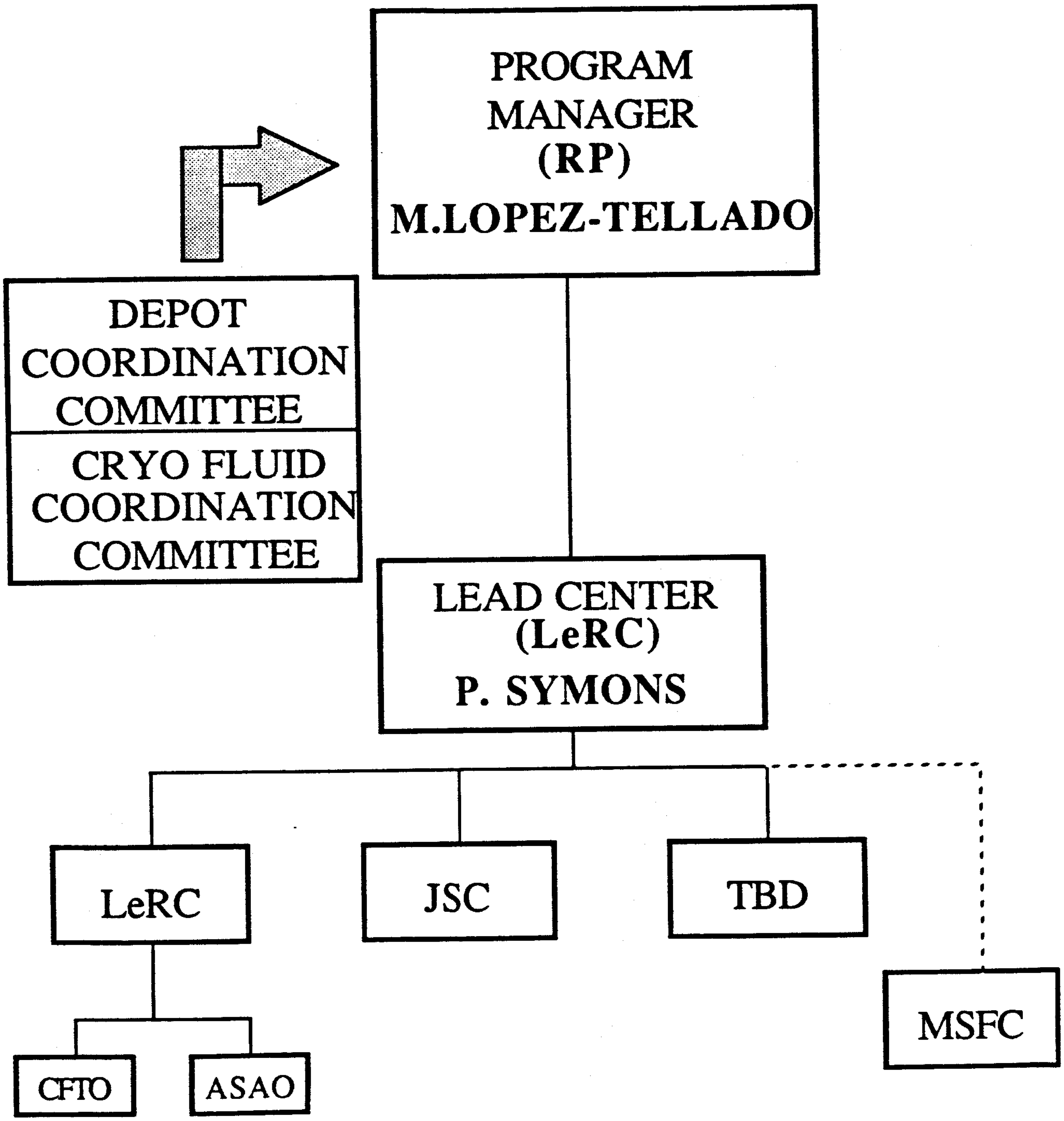


FIGURE 2-1 CRYOGENIC FLUID DEPOT PROGRAM MANAGEMENT STRUCTURE

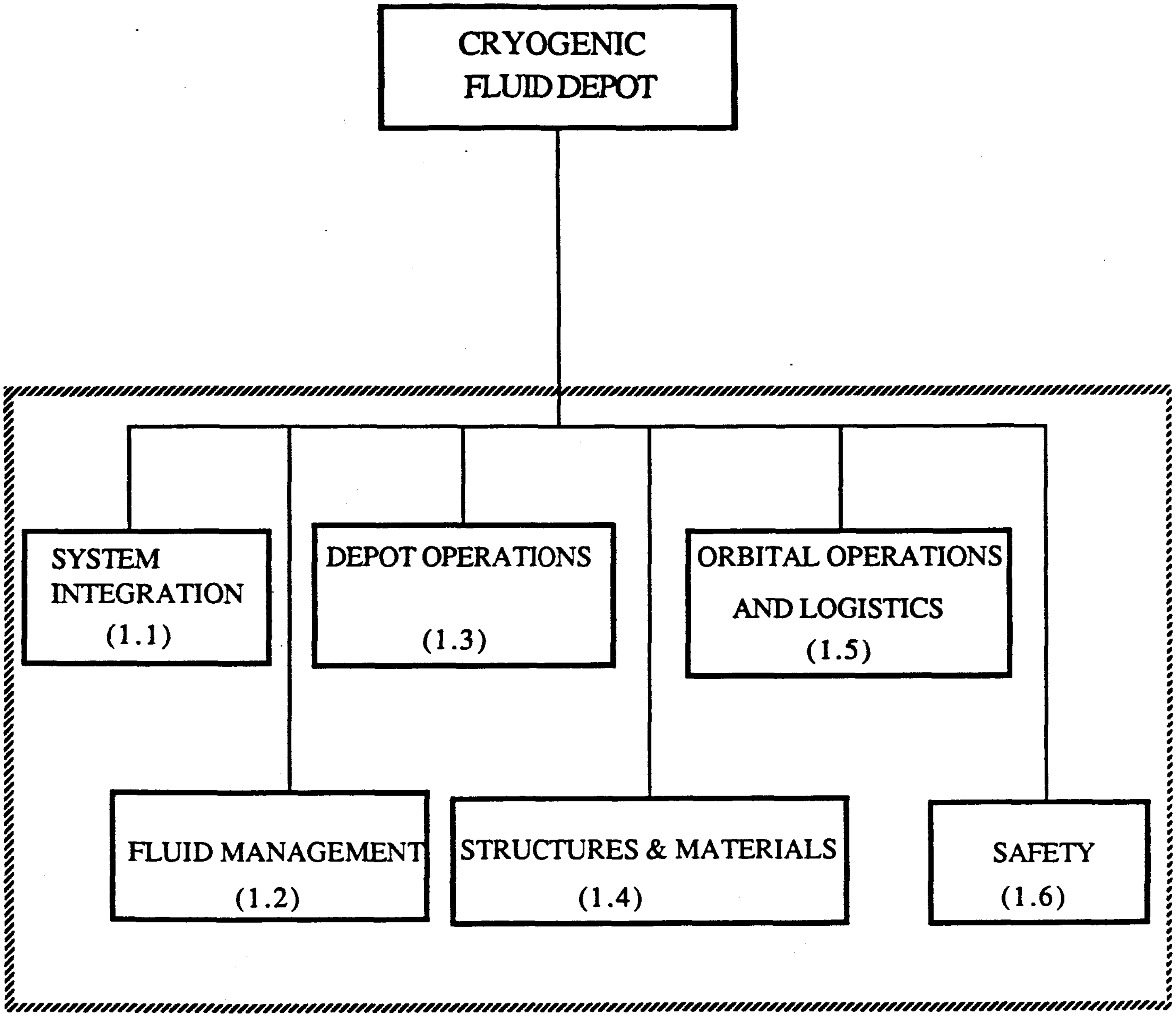
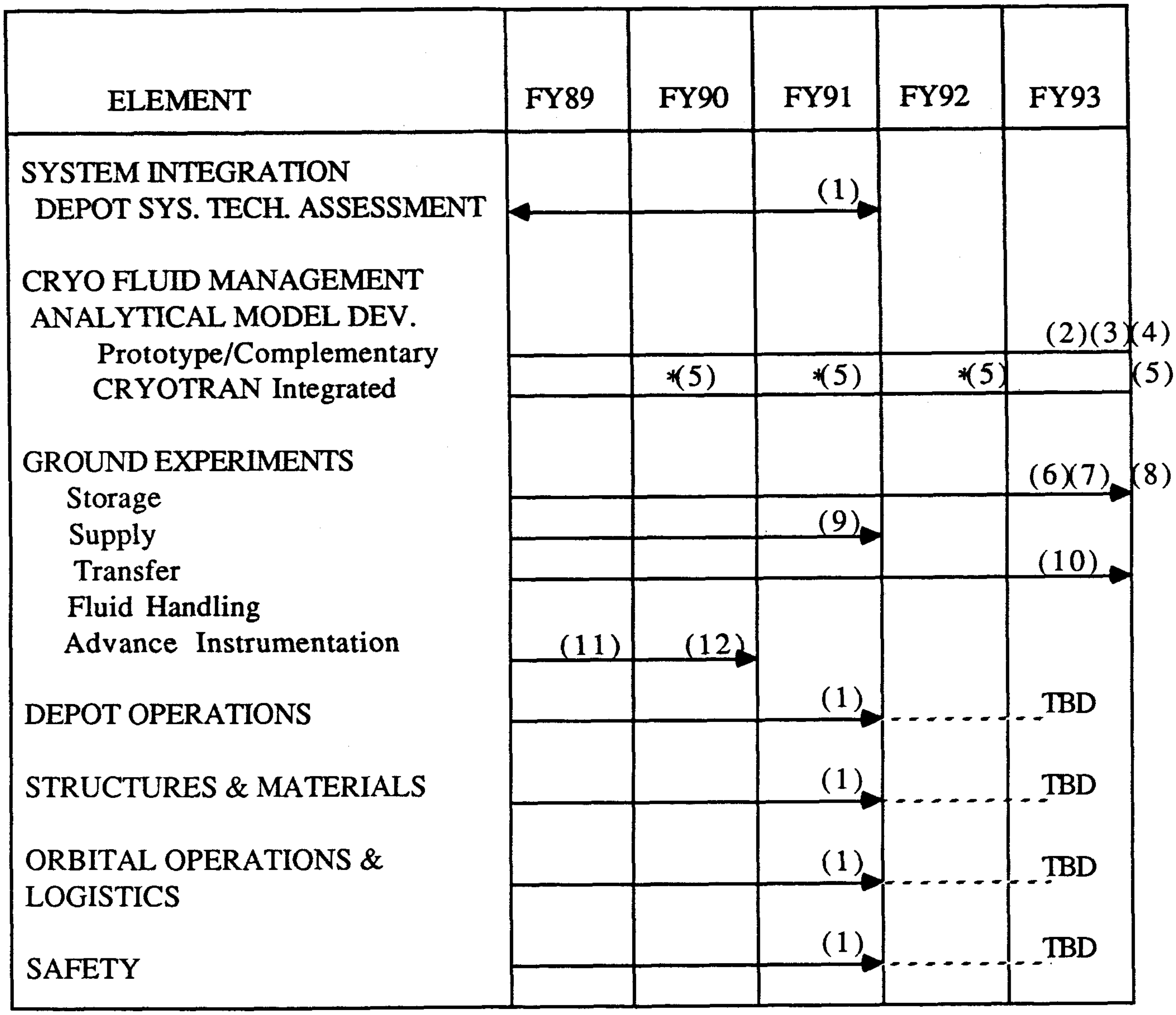


FIGURE 2-2 CRYOGENIC FLUID DEPOT PROGRAM WORK BREAKDOWN STRUCTURE



* Indicates version with partial 1-g validation

note: The meaning of the numbers are described in table 2-2

FIGURE 2-3 CRYOGENIC FLUID DEPOT PROGRAM FIVE YEAR SCHEDULE

Resources	Schedule (Fiscal Years)				
	1989	1990	1991	1992	1993
Funding ($, K)	3000	7000	5000	5000	5000
NASA Workforce (WY/Y)	22	23	23	23	23

TABLE 2-1 CRYOGENIC FLUID DEPOT PROGRAM PROJECTED RESOURCES

DELIVERABLE	DATE	* TECHNOLOGY READINESS LEVEL		
		START	COMPLETE	REQ'D
SYSTEM INTEGRATION				
Depot Technology Assessment				
(1) Detail Techn. Development Plan	1991			
CRYOGENIC FLUID MANAGEMENT				
Analytical Model Development				
(2) 1-g Supply Validated	1993	2	4	6
(3) 1-g Pressure Control Validation	1993	2	4	6
(4) 1-g Fluid Transfer Validation	1994	2	4	6
(5) CRYOTRAN Release w/1-g Validation	1994	2	4	6
Ground Experiments				
(6) 1-g Pressure Control Data Base	1993	2	4	6
(7) Depot Thermal Control T.A.	1993		N/A	
(8) Storage Thermal Control Dev.	1996	4	6	6
(9) 1-g Supply Data Base Completed	1991	3	4	6
(10) 1-g Fluid Transfer Data Base	1993	2	4	6
(11) 1-g Test of LH2 Flowmeter Comp.	1990	3	5	5
(12) Quantity Gauging Device Dev.	1989	2	5	5
DEPOT OPERATIONS	TBD	-----	----	----
STRUCTURES & MATERIALS	TBD	-----	----	----
ORBITAL OPERATIONS & LOGISTICS	TBD	-----	----	----
SAFETY	TBD	-----	----	----

* Technology Readiness Levels defined in the overall Pathfinder Program Plan

TABLE 2-2 CRYOGENIC FLUID DEPOT PROGRAM MAJOR MILESTONE

APPENDIX A

References

1. R. Stubbs, R. Corban, A. Willoughby, "On-Orbit Fuels Depot Technology Roadmap," report prepared by NASA Lewis Research Center for the NASA Office of Aeronautics and Space Technology, January 1988.

2. Proceedings of "Cryogenic Fluid Management Technology Workshop," Volume I and II, Lewis Research Center, April 1987.